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*subject:* Mechanical Modeling of a WIPP Drum Under Pressure.

## Executive Summary

Mechanical modeling was undertaken to support the Waste Isolation Pilot Plant (WIPP) technical assessment team (TAT) investigating the February 14th 2014 event where there was a radiological release at the WIPP. The initial goal of the modeling was to examine if a mechanical model could inform the team about the event. The intention was to have a model that could test scenarios with respect to the rate of pressurization. It was expected that the deformation and failure (inability of the drum to contain any pressure) would vary according to the pressurization rate. As the work progressed there was also interest in using the mechanical analysis of the drum to investigate what would happen if a drum pressurized when it was located under a standard waste package. Specifically, would the deformation be detectable from camera views within the room.

A finite element model of a WIPP 55-gallon drum was developed that used all hex elements. Analyses were conducted using the explicit transient dynamics module of Sierra/SM to explore potential pressurization scenarios of the drum. Theses analysis show similar deformation patterns to documented pressurization tests of drums in the literature. The calculated failure pressures from previous tests documented in the literature vary from as little as 16 psi to 320 psi. In addition, previous testing documented in the literature shows drums bulging but not failing at pressures ranging from 69 to 138 psi. The analyses performed for this study found the drums failing at pressures ranging from 35 psi to 75 psi. When the drums are pressurized quickly (in 0.01 seconds) there is significant deformation to the lid. At lower pressurization rates the deformation of the lid is considerably less, yet the lids will still open from the pressure. The analyses demonstrate the influence of pressurization rate on deformation and opening pressure of the drums.

Analyses conducted with a substantial mass on top of the closed drum demonstrate that the drums will still open provided the pressure is high enough. Investigation teams should look for displaced drum lids when searching for drums that have pressurized and failed.

The mechanical modeling study for this program is summarized in the following memo. Following a brief introduction, there is a summary of a brief literature review of previous pressure testing of drums, an explanation of the model, presentation of the key results, some discussion, and concluding with a summary and key points.

## Introduction

On February 14th 2014 there was a radiological release event at the Waste Isolation Pilot Plant (WIPP). An initial accident investigation report has been published which describes the event (U.S. DOE, 2014). An Accident Investigation Board (AIB) was created and as part of that board there is a Technical Assessment Team (TAT). The following work was conducted as part of Sandia National Labs (SNL) participation in the TATs effort.

Initial images obtained from within WIPP discovered one drum that appeared open. An image of this drum (drum 68660) is shown in Figure 1.

**Figure 1.** Drum 68660 in WIPP.

The following memo describes the mechanical modeling that was undertaken at SNL to support the TAT. The initial goal of this modeling was to examine if a mechanical model could inform the team about the event and specifically what happened within drum 68660. The intention was to have a model that could test scenarios with respect to the rate of pressurization. It was expected that the deformation and failure (inability of the drum to contain any pressure) would vary according to the pressurization rate. As the work progressed there was also interest in using the mechanical analysis of the drum to investigate what would happen if a drum pressurized when it was located under a standard waste package. Specifically, would the deformation be detectable from camera views within the room.

## Review of Previous Drum Pressure Testing

An initial literature review was conducted to determine if there was previous test data that could provide an indication of failure pressure and to provide results to benchmark the model developed for this work. Three studies were found that appeared relevant.

*Los Alamos National Labs pressurization tests*: A number of documents (Larranaga et al., 1998, Larranaga and Volz, 1998, Larranaga et al., 1999) appear to reference the same series of tests. Key points from this work are as follows:

1) The metal 55-gallon Open-Head drums tested in this work have the UN/DOT specification of 1A2/Y1.5/150. The WIPP drums modeled have the UN/DOT specification of 1A2/Y1.5/175. The difference is the wall thickness. The drums in the LANL study had a 1.2 mm nominal thick wall while the WIPP drum reportedly has a nominal wall thickness of 1.5 mm. A general internet search of drums suggests that some suppliers use the same lid thickness (1.5 mm) on both of these drums.
2) Failure pressures were similar for ½-full and ¾-full (with water) drums. Approximately 25-36 psi.
3) Failure pressures for cement filled drums was lower. Approximately 16-26 psi.
4) Drums failed near the bolt on the closure ring.
5) As quoted from LA-98-2541, "One interesting observation is the open-head drums appear to have vented at the above pressures immediately adjacent to the nut and bolt fastener on the ring."

*Savannah River pressurization tests*: These tests were documented in Dykes and Meyer (1991). Key points from this work are as follows:

1) The objectives of this testing was to determine the minimum hydrogen concentration at which lid removal will occur and to investigate the maximum pressure and rate of pressure rise as a function of hydrogen concentration.
2) As quoted from the report, "variability in drum lid sealing and retaining ring closure" prevented them from establishing a relationship between pressure and hydrogen concentration for the explosive tests. This suggests there is variability in the failure pressure.
3) Lids "blown" at pressures of 105-320 psi. Bulged at pressures of 69-138 psi.

*Lawrence Livermore National Laboratory Fire Testing of 55 Gallon Metal Waste Drums*: These tests were documented in Hasegawa et al. (1993).

Key points from this work are as follows:

1) Six tests were conducted using three different types of drums.
2) "Failure of the lid seals occurred in all of the drums early in the tests. Hot combustible gases vented from each drum and ignited. In three tests the lids blew off the drums ejecting some of the material from the drums."
3) "Failure of lid seals will allow release of any toxic and/or radioactive materials and smoke contained in the drums."

## Model Development

***Geometry:***

The drum modeled was created from specifications of a Skolnik open head carbon steel drum, item CQ5508 (Skolnik, 2014). Drawings for the drum, lid, and bolt ring were obtained (see Appendix). Based on these drawings and some general assumptions a CAD file was created of the geometry. This file was used to create the meshes discussed below. The key assumption where the model differs from the actual geometry is in the ribs on the drum wall. Exact descriptions of those ribs are not detailed in on the drawings and the geometry of the ribs was simplified for speed of construction of the CAD geometry. The geometric differences of the ribs between the actual drum and that modeled are not considered significant with respect to the failure pressure and lid deformation behavior since they will mostly influence the circumferential stiffness of the drum. Figure 2 shows an overview of the geometry created and a section of the drum CAD geometry.

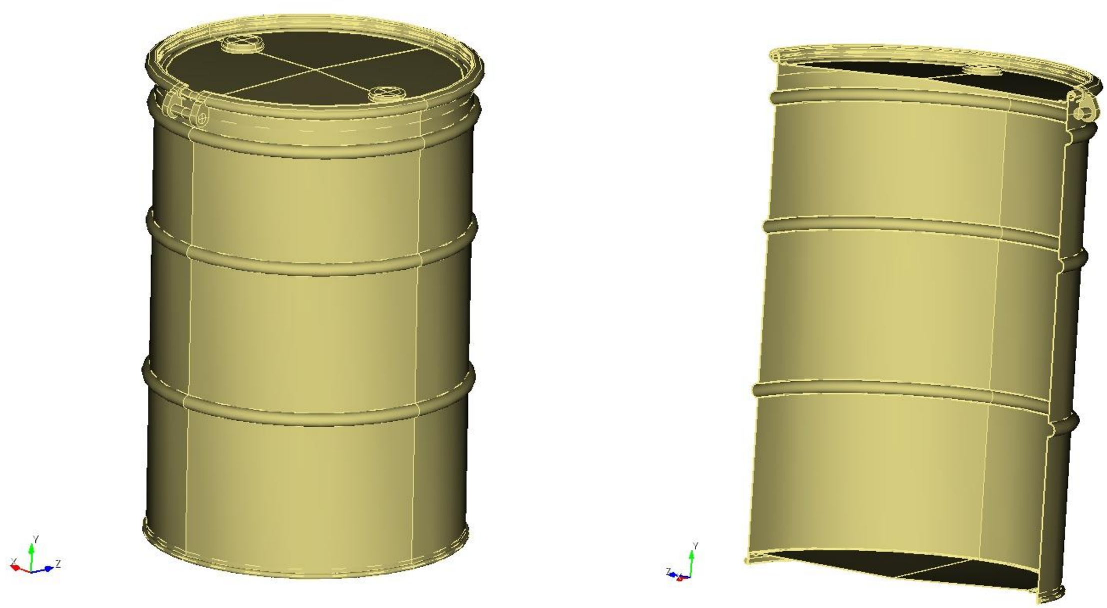

**Figure 2.** Skolnik CQ5508 Drum CAD geometry.

***Material Properties:***

An initial estimate of mechanical properties of the drum material was based on properties from Ludwigsen, et al (1998) except the yield strength was lowered to 29.0e03 psi to more closely match published values (AKsteel, 2014) of yield strength for ASTM A1008 steel used in these drums. Eventually, specimens were cut from the lid and closure ring of a drum obtained from LANL and tensile tests were performed on these specimens. The specimens tested from the drum lid were standard ASTM E8 sheet type specimen (ASTM, 2013). The specimens tested from the closure ring were ASTM E8 miniature specimens (ASTM, 2013).

There was not significant variation between each of the three specimens tested for each material. Figures 3 and 4 present the engineering stress-strain plots for the test data. The data for test 2 of each material was used in the analyses. For the closure ring data the material had a yield strength of 30.5e03 psi and for the drum lid material it had a yield strength of 40.0e03 psi. The ELASTIC_PLASTIC material model in

Sierra/Solid Mechanics (Sierra Solid Mechanics, 2014) was used for the analyses. The hardening curves from the test data were implemented in the analyses for the elastic-plastic model. Figures 3 and 4 each have the initial assumed yield strength marked to demonstrate the difference between the initially assumed values and those of the tested properties from the drum obtained from LANL.

The initial analyses used the same properties for all material blocks in the model. Therefore, the drum body, lid, closure ring, and bolt all had the same properties (yield strength of 29.0e03 psi). The analyses run using the tested properties were run with the properties of the closure ring for the model closure ring and bolt, while the drum lid properties were used for the models drum body and the drum lid.

In all cases the gasket that is between the lid and the drum body lip is included in the analyses. However, it is modeled as steel. Modeling the gasket as a soft rubber presents computational difficulties. The gasket was included in the model to make sure the lid is seated accurately, but without the compliance of the rubber.

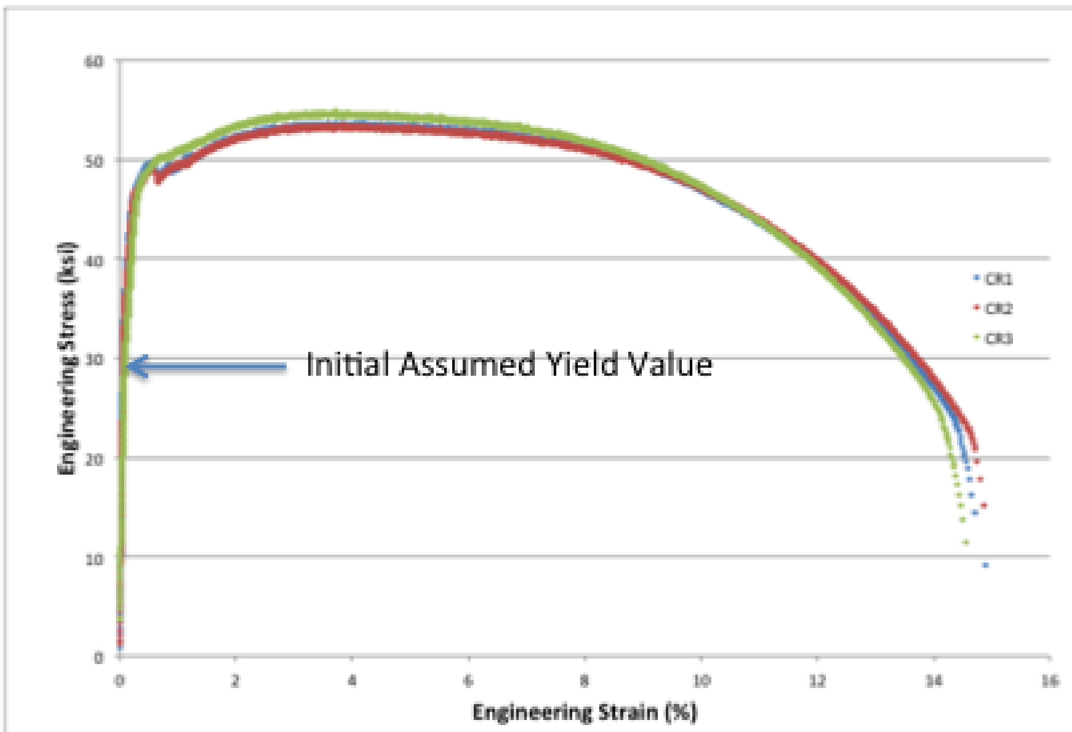


**Figure 3.** Tested Closure Ring Engineering Stress-Percent Strain Curves for a drum obtained from LANL.

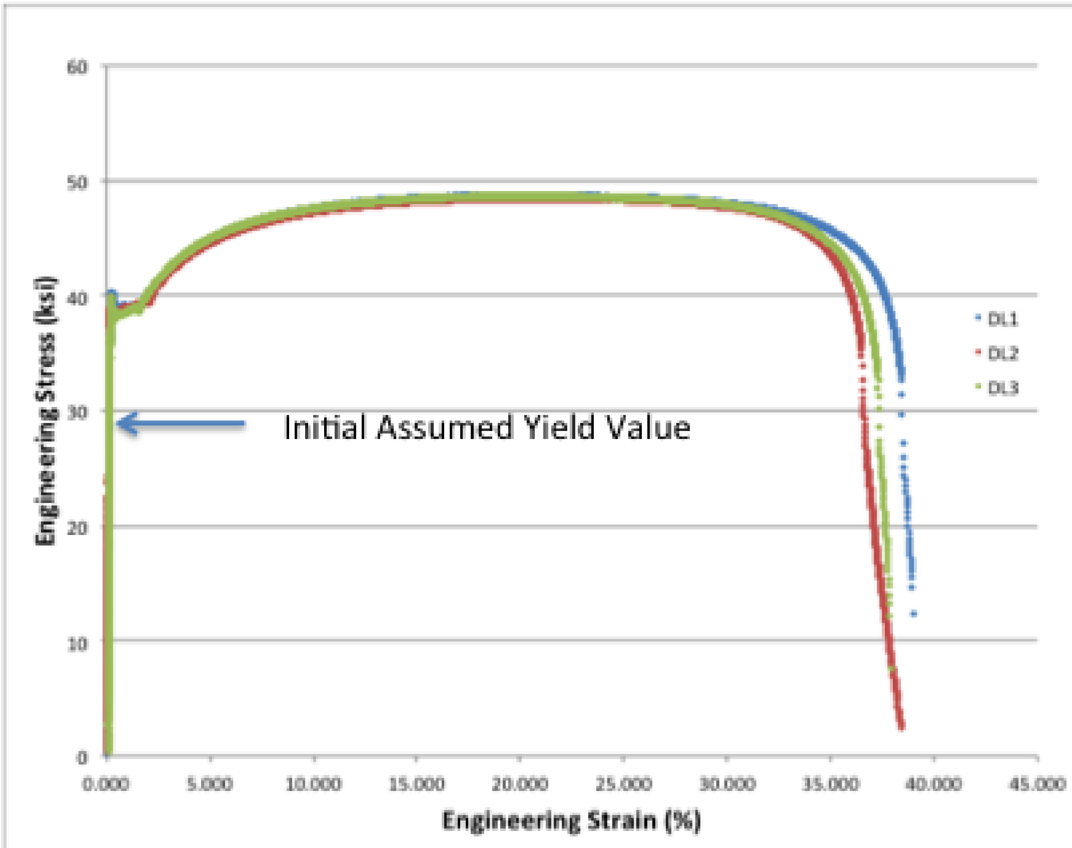


**Figure 4.** Tested Drum Lid Engineering Stress-Percent Strain Curves for a drum obtained from LANL.

***Analysis Approaches Explored:***

The finite element meshes were created using Cubit (Cubit, 2014) and the analyses were performed using Sierra/SM (Sierra/SolidMechanics, 2014).

Multiple analysis approaches were pursued initially to come up with an approach that could provide solutions within the accelerated timeframe and to maximize/optimize the potential solution methods. Options such as a full hex mesh, a hex-to-shell transition mesh, and pure shell mesh were pursued. In addition, the options for applying the preload to the drum closure ring to provide a tightly closed drum were pursued by both applying a closure strain to the closure ring and by displacing the flanges of the closure ring within the analysis and having the ring tighten due to the displacement; followed by securing the bolt (using the "tied" contact option in the code). Finally, the options of using either an implicit solver or performing a explicit transient dynamic analysis were pursued.

The advantage of using the implicit solver is that it can solve the analysis with larger time steps. This allows one to solve a problem over a much longer time frame than a transient dynamic analysis that takes many very small steps. However, the implicit solver can have trouble converging where there is significant contact. The problem of pressurizing a drum and having the solution run until the drum opens by the closure ring sliding over the lip of the drum body is a complex contact problem.

In the end, the full hex mesh using the explicit transient dynamic solutions was the only approach that yielded solutions under the current budget/time constraints. This approach provided a robust solution that has two main drawbacks. One, the turn-around time for analyses was slow, the solutions took 1-4 days of runtime. The model had more than 8-million elements with a time-step of approximately 2.3e-08. Therefore, the turn-around time for analyses did not allow a substantial number of analyses. Second, due to the small time-step and duration of the event, only short duration events could be examined and consequently, what happens after the lid opens is beyond the reasonable duration of run-time. In addition, what happens after the drum lid opens is a very complex process that is beyond the fidelity of this model. This model does not include the contents under pressure and cannot account for the loss of pressure once the drum opens.

Modeling the closure of the drums is only an approximation of what the actual drums go through in the specified closure procedure. To have a more accurate representation of the drum closure preload for these analyses it would be best to have a measure of the strain in the closure ring once the drum is closed per the specified procedure. Since that was not available, the drum closure ring flanges were displaced to a position that resembled that of closed drums. However, small variations in this distance could potentially have a measurable influence on the preload of the closure ring (and opening pressure). In addition, the gasket between the drum lip and the lid likely changes the frictional characteristics between the parts and will have some influence on the opening pressure for these calculations. A coefficient of friction of 0.3 was modeled between all parts for these analyses.

### *Applied Loading:*

A number of loading cases were explored for the analyses. For the pressurization two main cases were considered. Figures 5 and 6 present schematics of the two basic loading cases. The maximum pressure of the applied loadings varied some, but the shapes of the pressure curves were the same. For the analyses, this pressure was applied to the inside of the drum on the bottom, sidewall, and inside of the lid. When specific cases are discussed below, the maximum pressure will be specified. Figure 5 shows what will be referred to as the “slow” loading case. For these cases the closure ring is closed in 0.005 seconds. Then the pressure is steadily increased until the time has reached 0.1 seconds. The other case (shown in Figure 6), referred to as the “fast” load case the closure ring is closed in 0.005 seconds. Then the pressure is ramped quickly up to a “maximum” pressure at a total time of 0.015 seconds. Then, simulate pressure release, ramped back to zero in another 0.001 seconds (total time of 0.016 seconds). Some cases varying the time to maximum ramp pressure were also performed. Both of these pressure cases are purely hypothesized in nature, i.e. no chemistry effect should be inferred for these cases. They are used to understand structural performance differences that might present themselves from a short burst or a longer term loading.

The acceleration of gravity was applied in all of the cases presented below. In addition, the estimated weight of the contents (for drum 68660) was included as a downward pressure on the bottom of the drums. For some analyses, a hydrostatic pressure on the sidewalls was applied to account for the contents applying pressure on the sidewalls. This was done because some of the testing at LANL (drums filled with cement) failed at lower pressures. However, for the analyses conducted with this study that included this hydrostatic sidewall pressure, the results were not affected. Therefore, further analyses did not include this loading.

Analyses were also conducted with a pressure force on the lid to account for the mass of the magnesium oxide (MgO). However, it should be noted that since this is applied as a pressure force down there are no inertial forces from this loading. The pressure to account for the weight of the MgO is 1.54 psi uniformly applied to the top of the drum. This is small compared to the internal pressure.

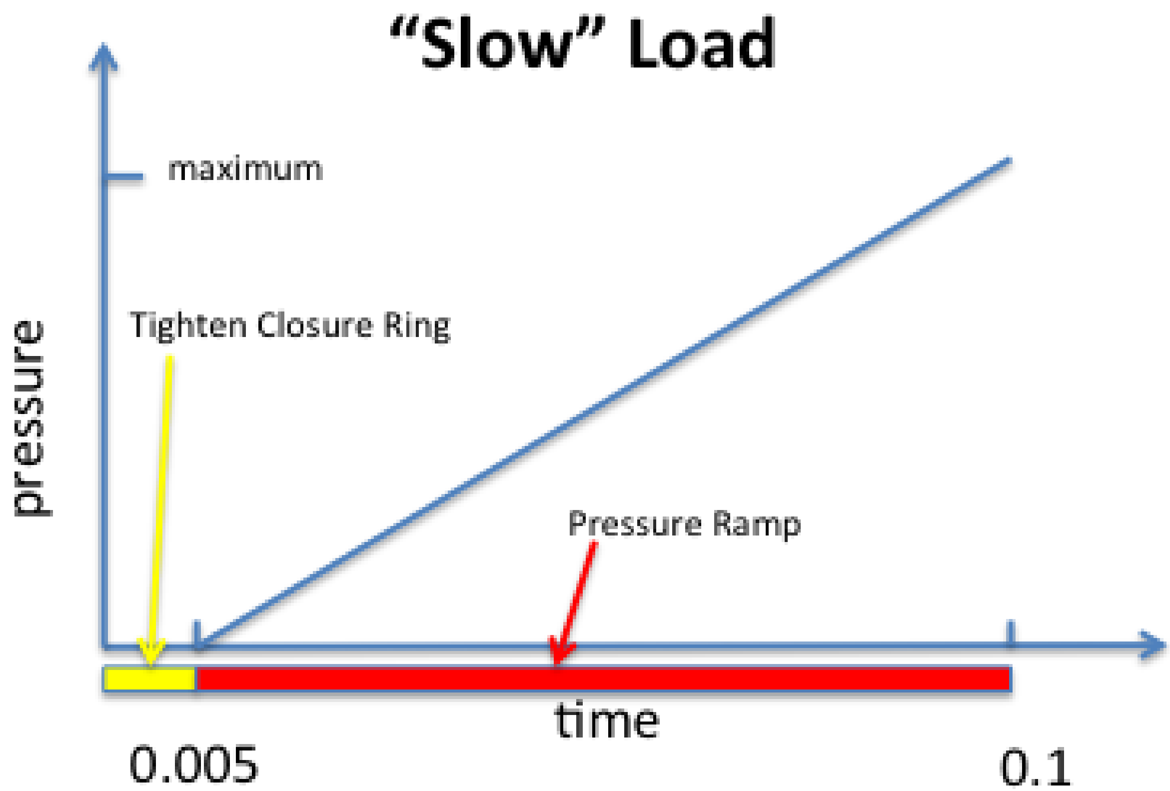


**Figure 5.** Slower ramped loading form for analyses (referred to as “Slow” load).

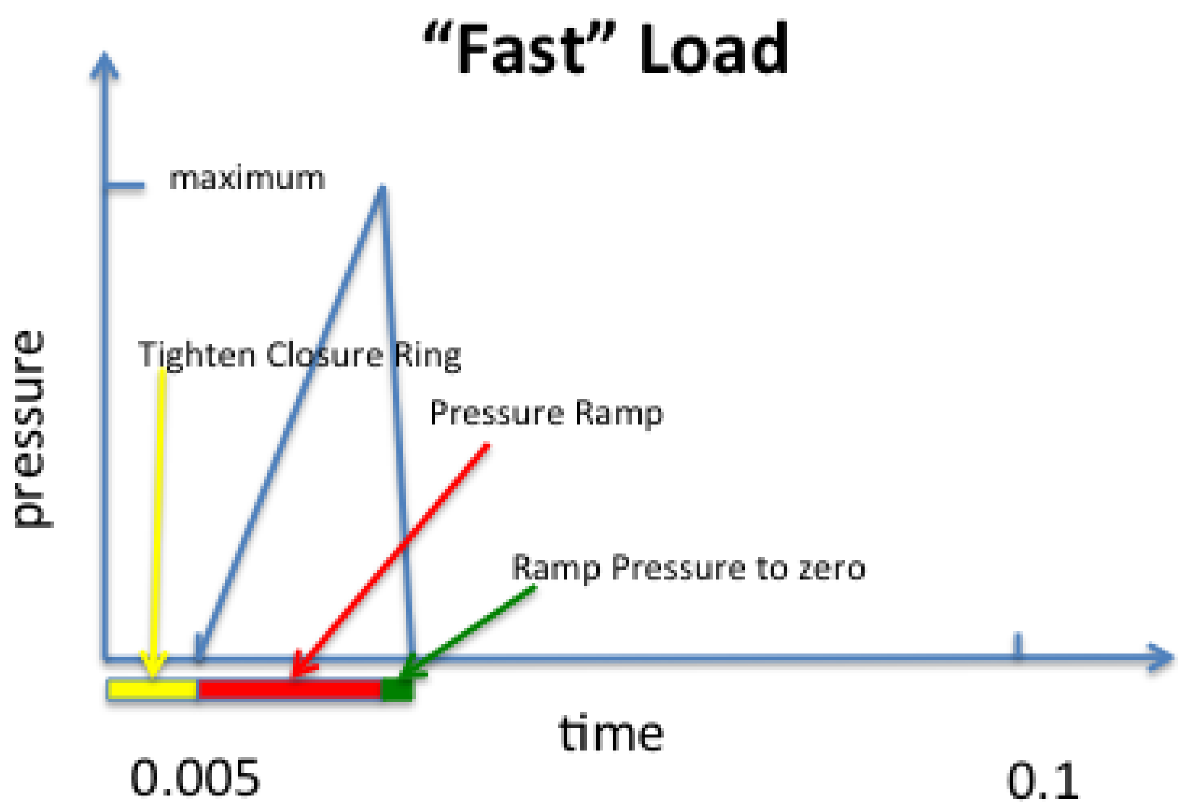


**Figure 6.** Faster ramped loading form (and unloading) for analyses (referred to as “Fast” load).

## Key Analysis Results

Since there is some subjectivity in the preload of the closure of the drums in these analyses (and most likely in actual drums) the predicted opening pressure also has some uncertainty. However, despite this issue there are a number of key results to present and conclusions that can be drawn from the result. In addition, results for the two different property sets (initially estimated properties and those from tests of a single drum from LANL) provide insight into potential variation in behavior such as deformation and failure pressure. Therefore, presented here are results of a number of the analyses preformed for this study.

*Using original mechanical property estimate and "fast" load case*: For this case the maximum pressure load corresponds to 150 psi. The lid "pops" open at a pressure of approximately 75 psi. In the analysis the pressure continued to rise as the lid continued to come off. In an actual event, the pressure would be relieved once the drum opened. Analyses similar to this were run where the pressure was reduced to zero as soon as the lid "popped" open. In those cases the lid continued to open until the end of the analysis at 0.1 seconds. When the lid opens it has considerable velocity and one would not expect it to slow down within the 0.1 seconds of these analyses. Figure 7 shows the drum with the Von Mises stress contours at the time the lid is opening (maximum contour represents yielding for the drum material). Note the large deformations of the lid. In addition, note the deformation near the closure-ring bolt. This lid deformation pattern is similar to the results from the testing at LANL (1998) with respect to the deformation pattern. Note that the separation of the closure ring from the lid is happening after the lid has opened. Since as stated above, the pressure is still being applied in the analysis which is likely not the case in an actual pressurization event (since the pressure would have been relieved) one can not be certain if the closure ring would actually separate from the lid.

Figure 8 shows a comparison of one of the drums tested at LANL (Larranaga et al., 1999) and the results of the analysis at a similar deformation state. One can see the deformation patterns are similar. In addition, Figure 9 shows a section from the analysis at the same point. There is actually a gap opened between the lid and the drum body lip where the closure ring gap is at the location of the bolt. This is where the drums lost pressure for the drums tested at LANL. In Figure 9, one can see the seal would still be maintained at the opposite side of the lid because the closure ring is in contact with the drum body lip (in a real drum the gasket would protrude out of the closure ring). Also note as pointed out in Figure 9, the discontinuity in the lid deformation patter near the plug location.

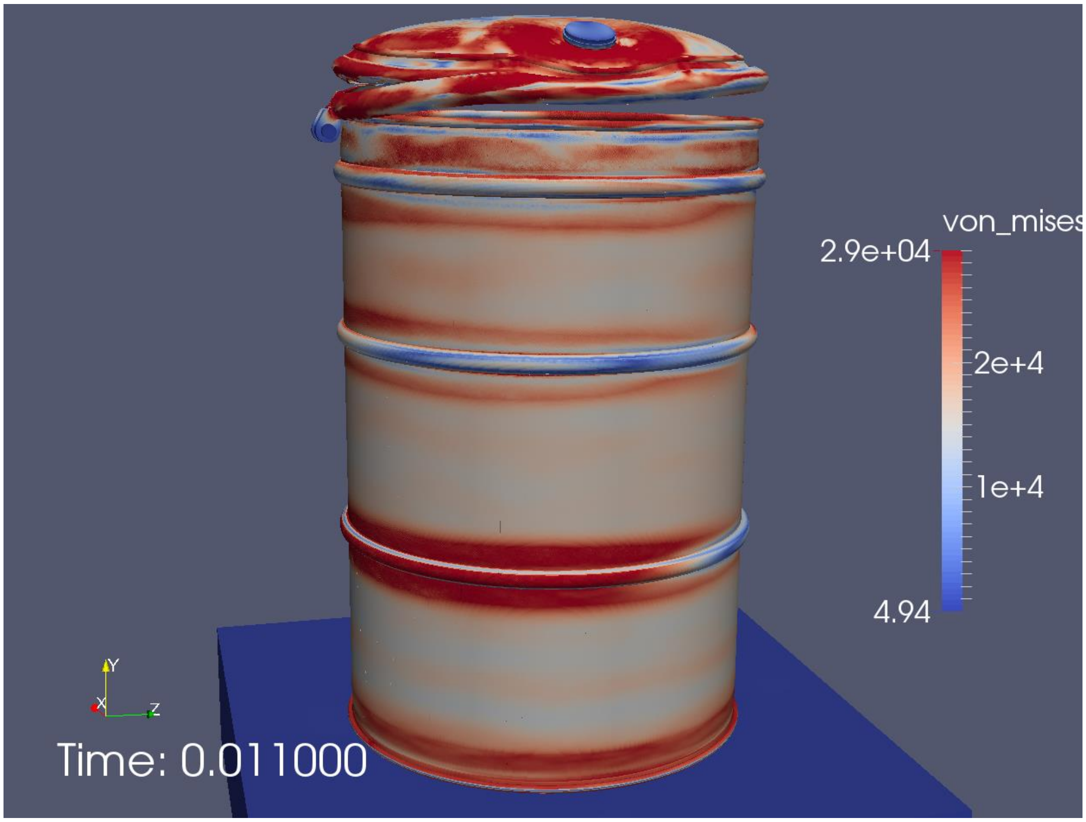


**Figure 7.** Analysis results for case with original estimate of properties and “fast” loading.

**Figure 8.** Comparison of tested drum at LANL (Larranaga et al., 1999) left, and analysis results, right.

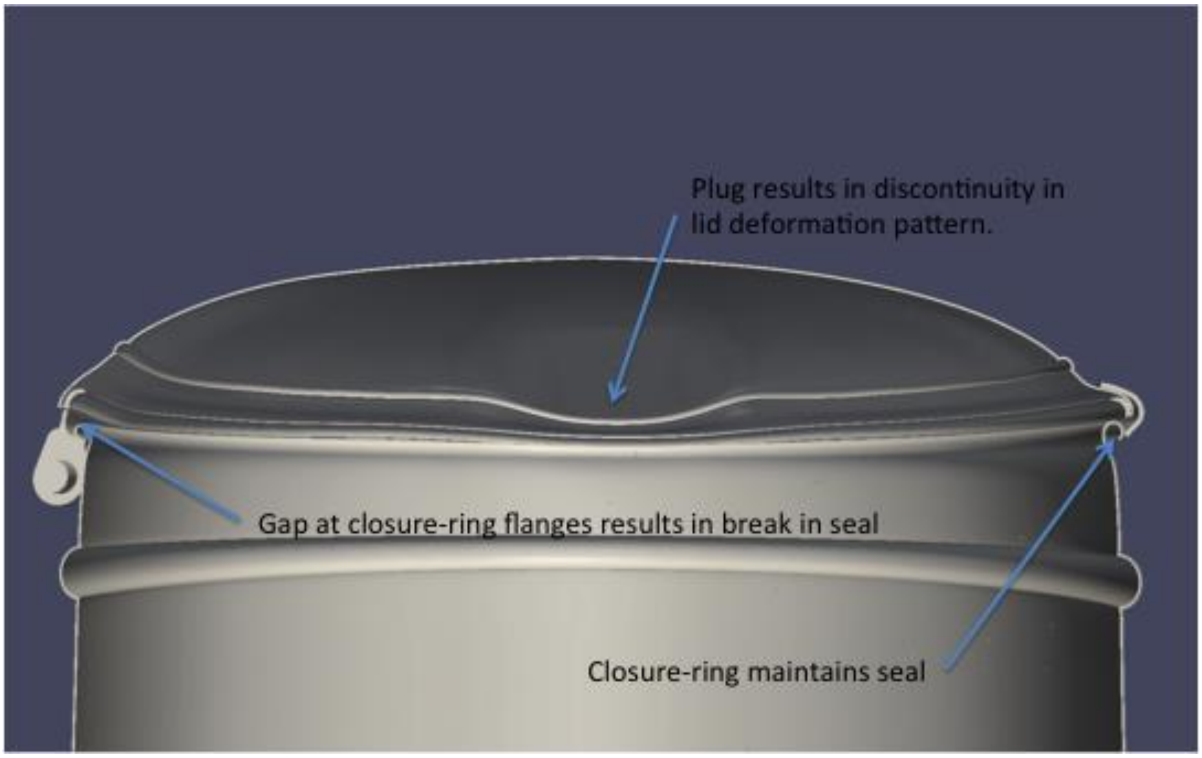

**Figure 9.** Section showing lid deformation for initial property estimates and "fast" loading case.

*Using original mechanical property estimate and "slow" load case*: For this case the maximum pressure load corresponds to 50 psi. The lid "pops" open at a pressure of approximately 35 psi. In the analysis the pressure continues to be applied as the lid comes off. In an actual event, the pressure would be relieved once the drum is open. As discussed above, cases were run where the pressure was reduced to zero once the lid opened. However, the velocity of the lid is still high as the lid opens and it continues to move up until the analysis is complete at 0.1 seconds. Figure 10 shows the drum with the Von Mises stress contours after the lid is open. In this "slow" loading case one can see there is less deformation of the lid when it opens then for the "fast" case. In addition, the lid opens in a gentler manner with the opening initiating away from the closure-ring bolt. Figure 11 shows the lid from another view as it is opening. At a pressure of 30 psi the maximum deformation at the center of the lid is 2.6 inches and for the testing at LANL for a ¾-full drum was measured at 2.8 inches. As pointed out above, the LANL tested drums were a thinner gauge material that could account for some of this difference.

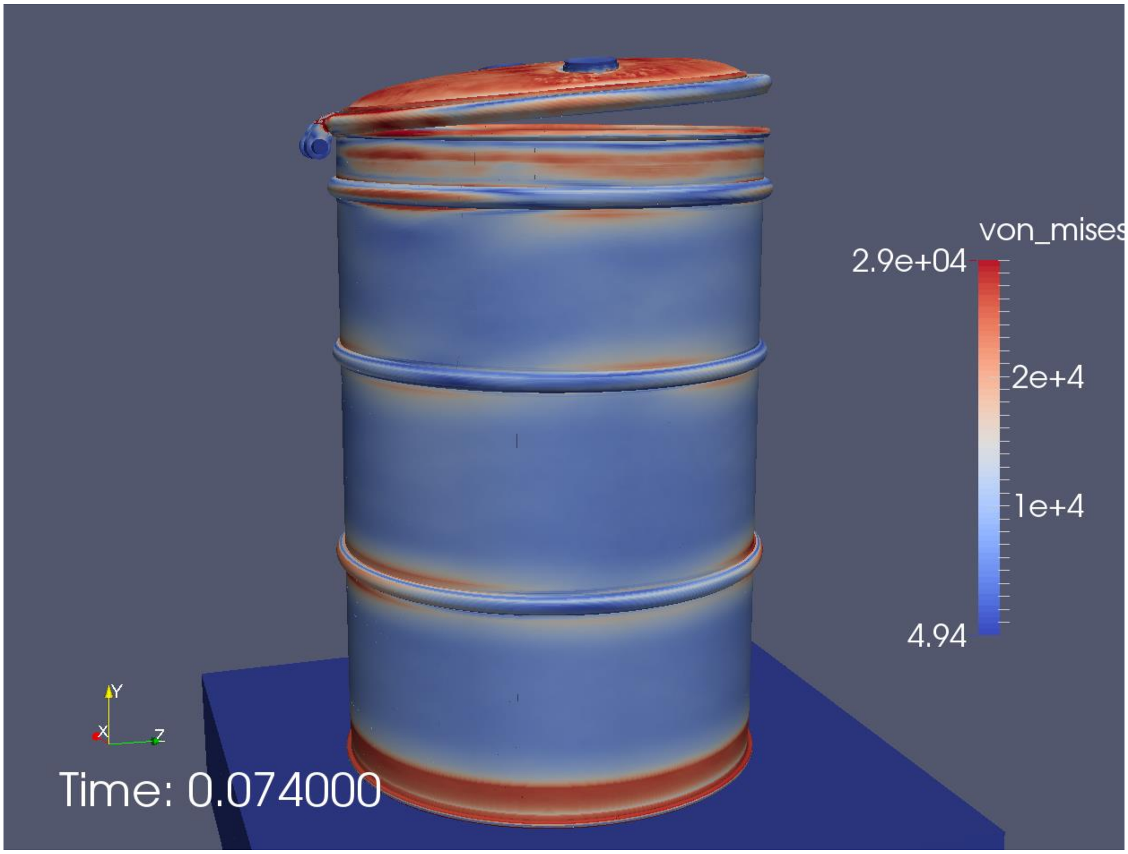


**Figure 10.** Analysis results for case with original estimate of properties and “slow” loading.

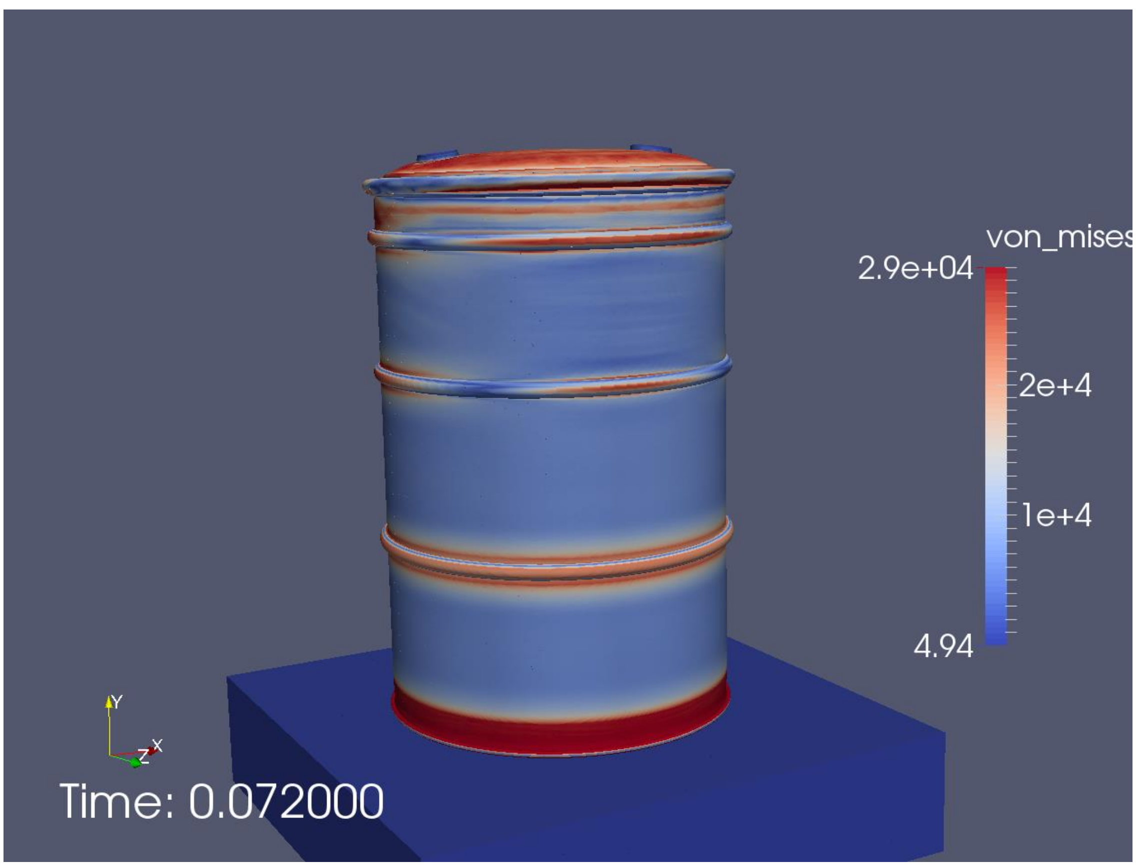

**Figure 11.** As opening (Figure 1 has it after it is open)

*Using original mechanical property estimates, "slow" load case, with surrogate drum on top*: For this case a surrogate drum was placed directly on top of the drum. This case was to provide some insight of what to look for if a drum under other waste packages was pressurized. The maximum pressure in this case was 50 psi. The drum opened at a pressure of approximately 46 psi. Once again, for this analysis the pressure continues to ramp up until 0.1 seconds. Figure 12 shows the drum after it has opened. As expected, it takes a greater pressure to open the closure, but only an additional 11 psi.

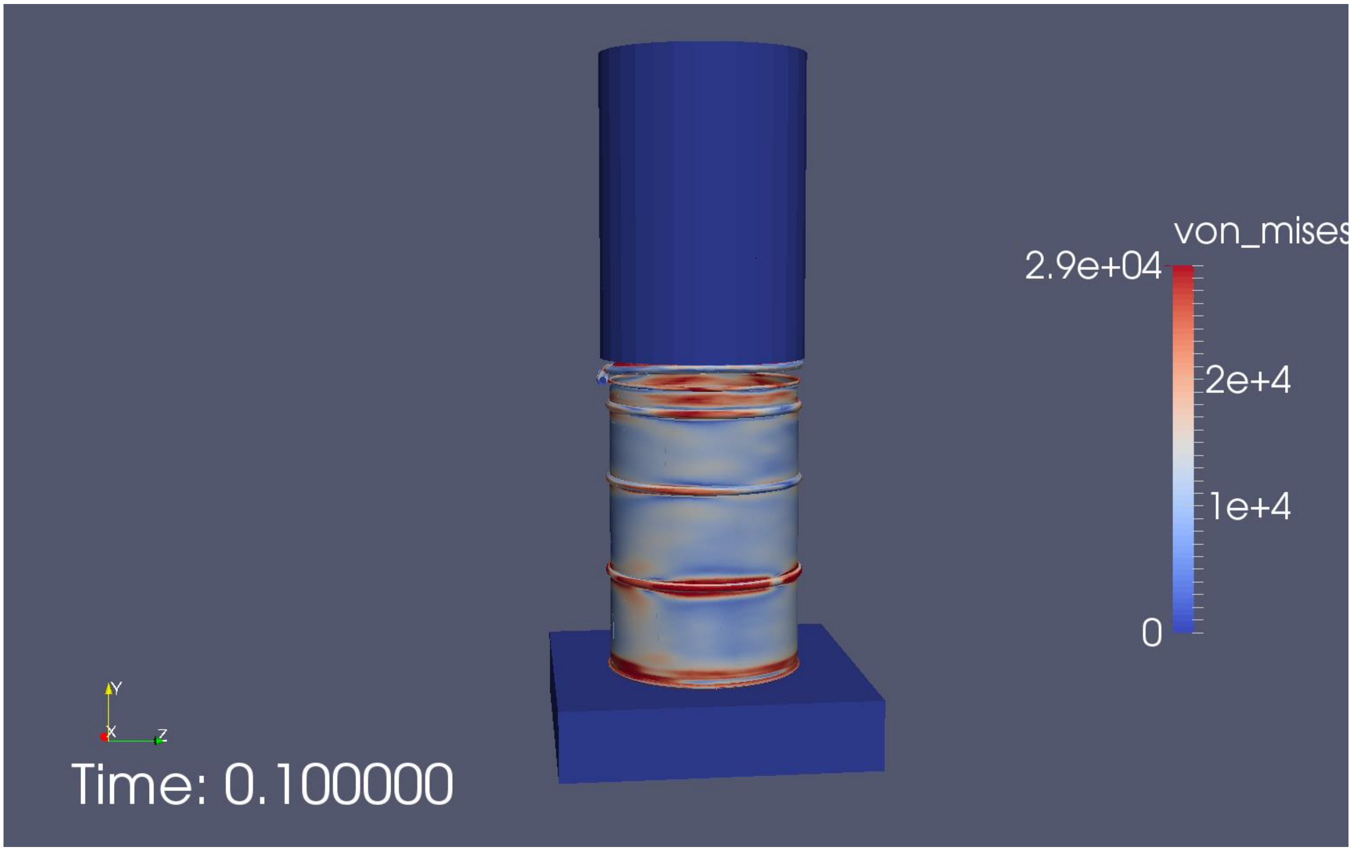


**Figure 12.** Analysis results for case with original estimate of properties, "slow" loading, and surrogate cask on top.

*Using test properties "fast" loading case*: For this case the maximum pressure of the ramp was 75 psi. Results presented in Figure 13. The deformation pattern of the lid as it opens is similar to the same loading case with the original estimated properties. The pressure when the drum lid pops off is approximately 75 psi, just as the case with the original estimated properties and the fast loading case.

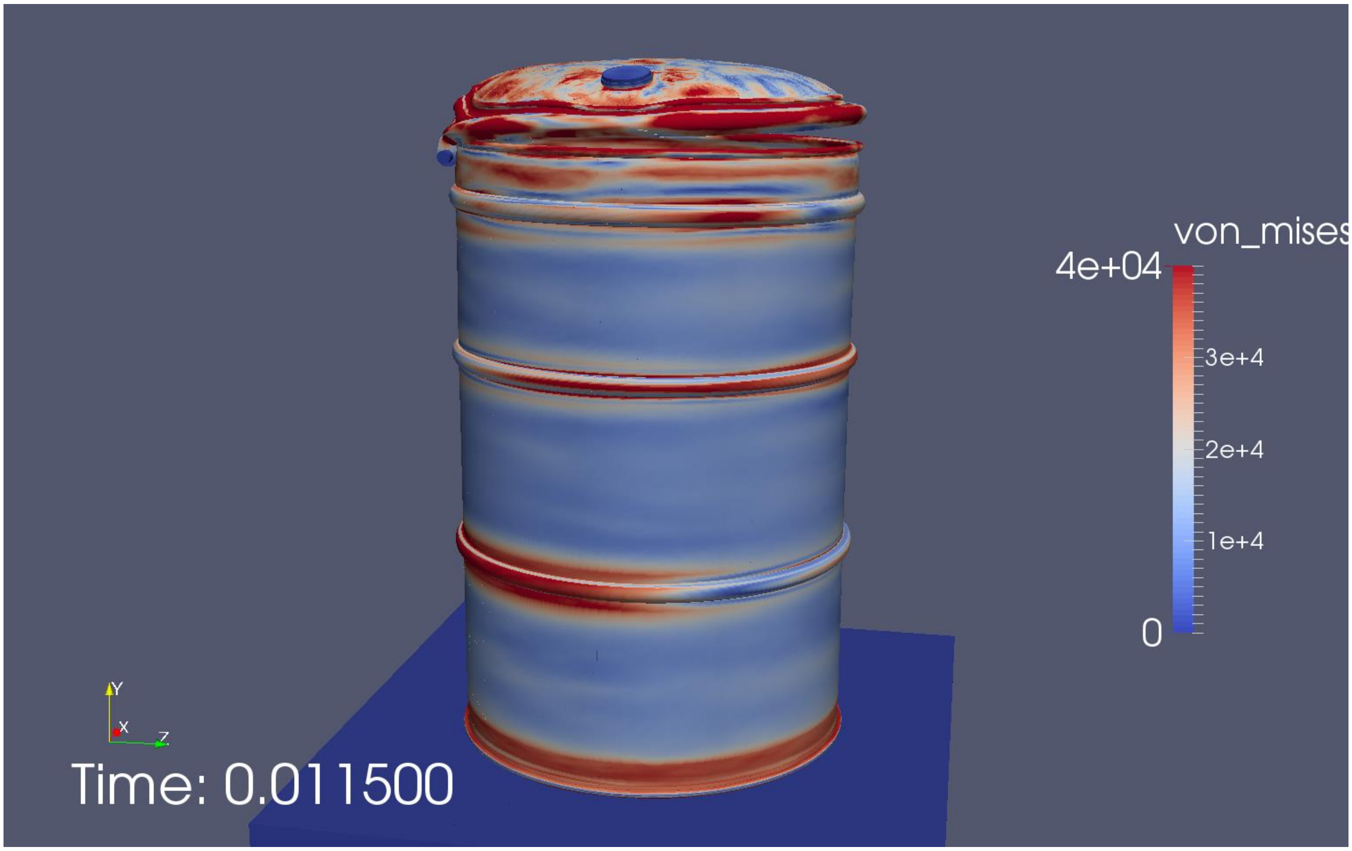

**Figure 13.** Analysis results for case with test properties and "fast" loading.

*Using test properties "slow" loading case*: Initially, the "slow" loading case was repeated with the same maximum pressure for the ramp pressure (50 psi). However, with the test properties this case did not vent. Subsequently, it was re-run with a maximum pressure of 75 psi. This case did vent at a pressure of approximately 58 psi. See Figure 14 (once again, the maximum contour represents yield for the drum material). The drum material for the test properties has a yield of 40.0e03 psi compared to the 29.0e03 psi used in the original estimate. See Figure 4 showing the test properties and previous estimated yield. At a pressure of 30 psi the maximum deformation at the center of the lid is 2.2 inches and for the testing at LANL for a ¾-full drum was measured at 2.8 inches. . As pointed out above, the LANL tested drums were a thinner gauge material that could account for some of this difference.

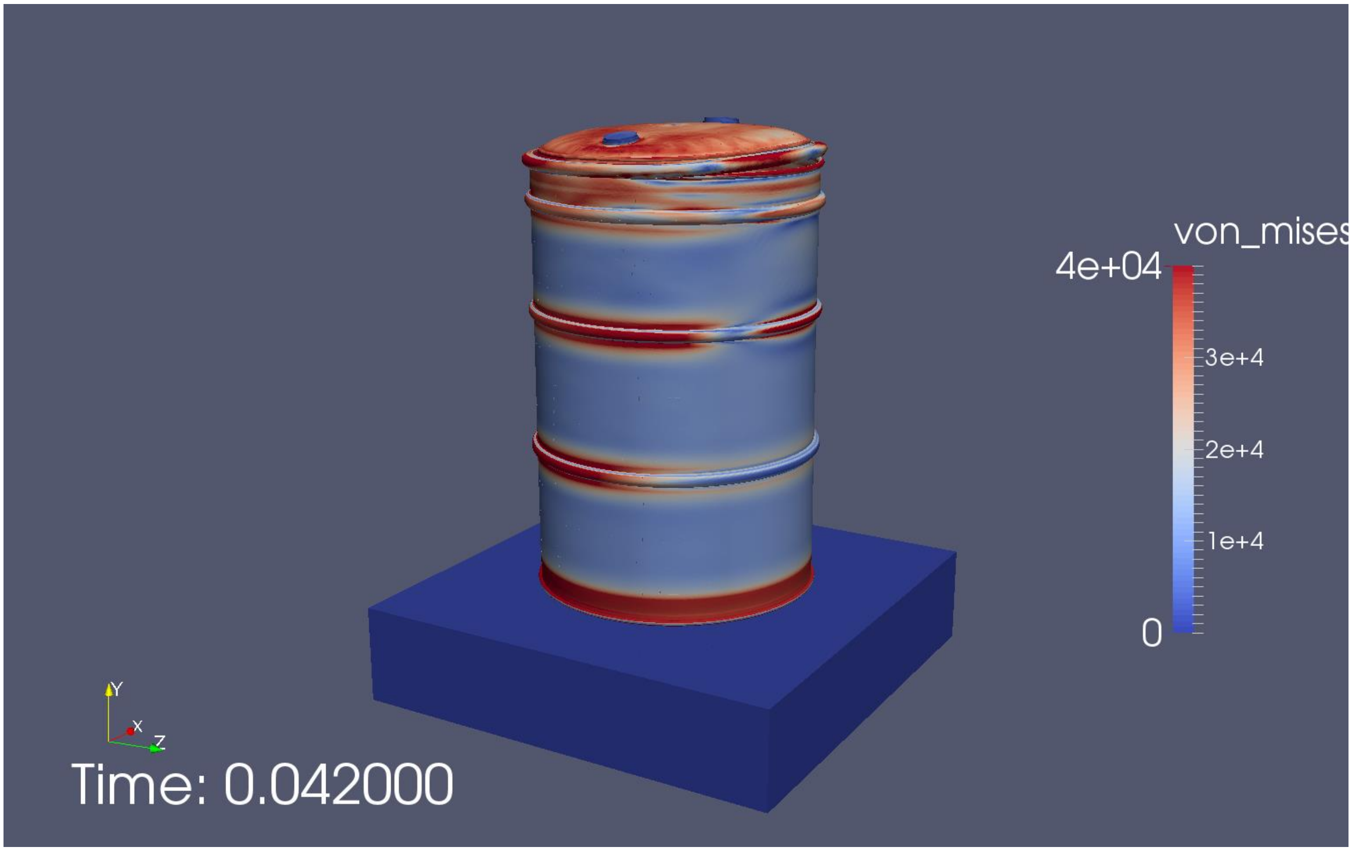


**Figure 14.** Analysis results for case with test properties and "slow" loading.

<u>*Using test properties "slow" loading case, with surrogate drum on top*</u>: The first analysis run for this case had a maximum ramp pressure of 50 psi. That case did not result in the drum venting. See Figure 15. The analysis was repeated with a max pressure of 75 psi. This case resulted in the drum venting at a pressure of approximately 67 psi (see Figure 16).

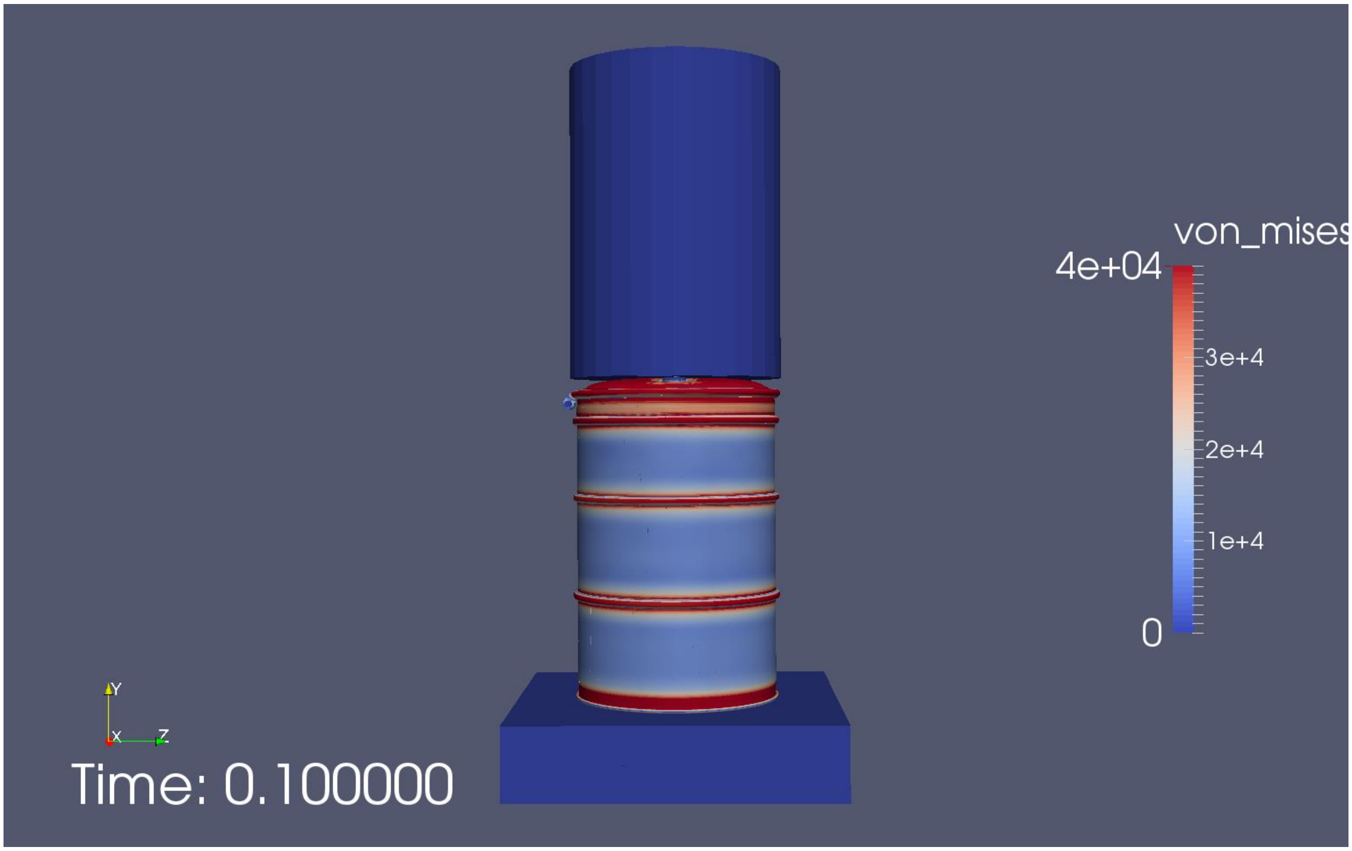


**Figure 15.** Analysis results for case with test properties, “slow” loading with maximum ramp pressure of 50 psi, and surrogate cask on top.

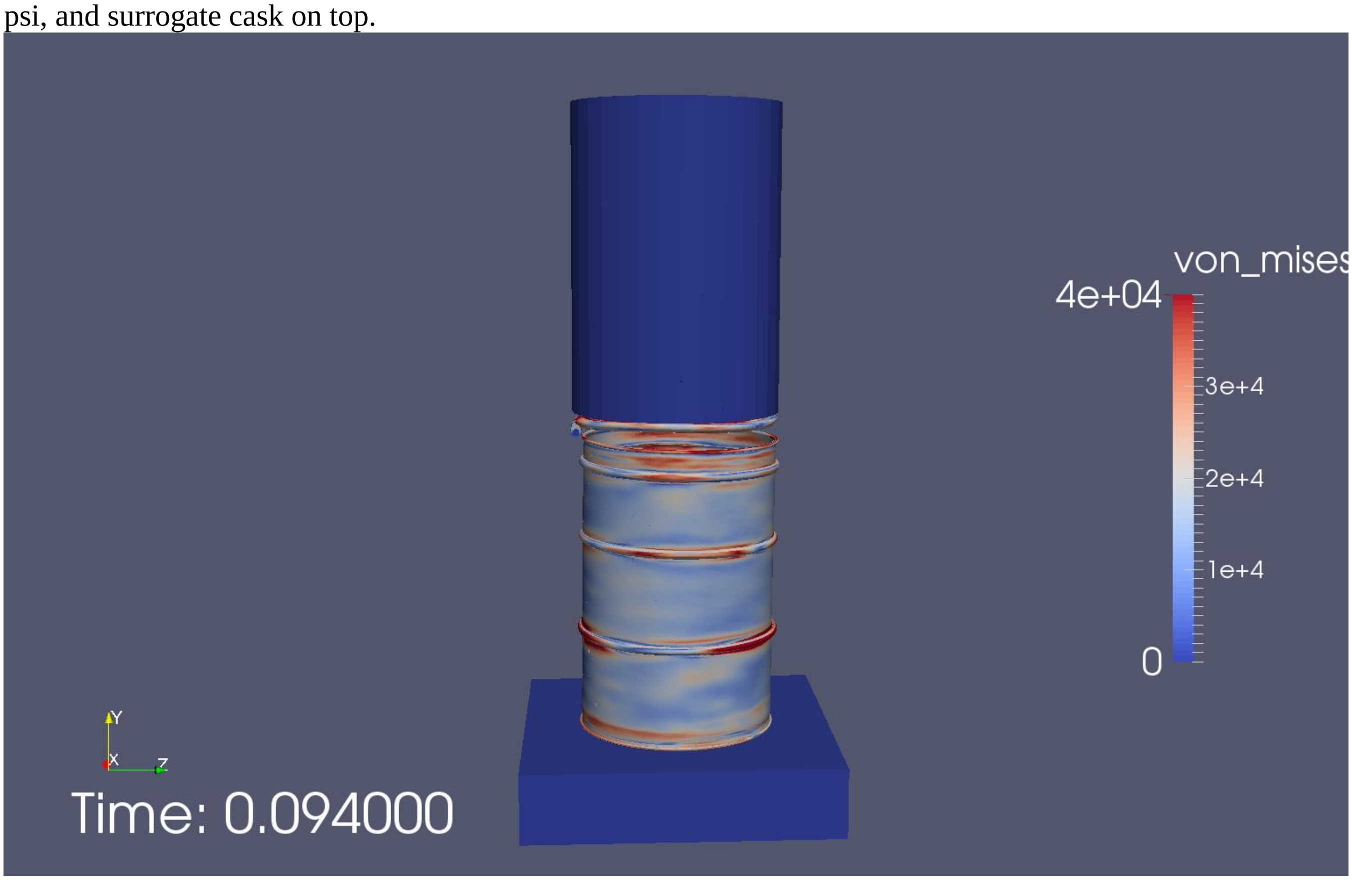

**Figure 16.** Analysis results for case with test properties, "slow" loading with maximum ramp pressure of 75 psi, and surrogate cask on top.

*Using test properties "fast" loading case, with surrogate drum on top*: This case was run with a maximum ramp pressure of 75 psi and the drum did not vent (see Figure 17).

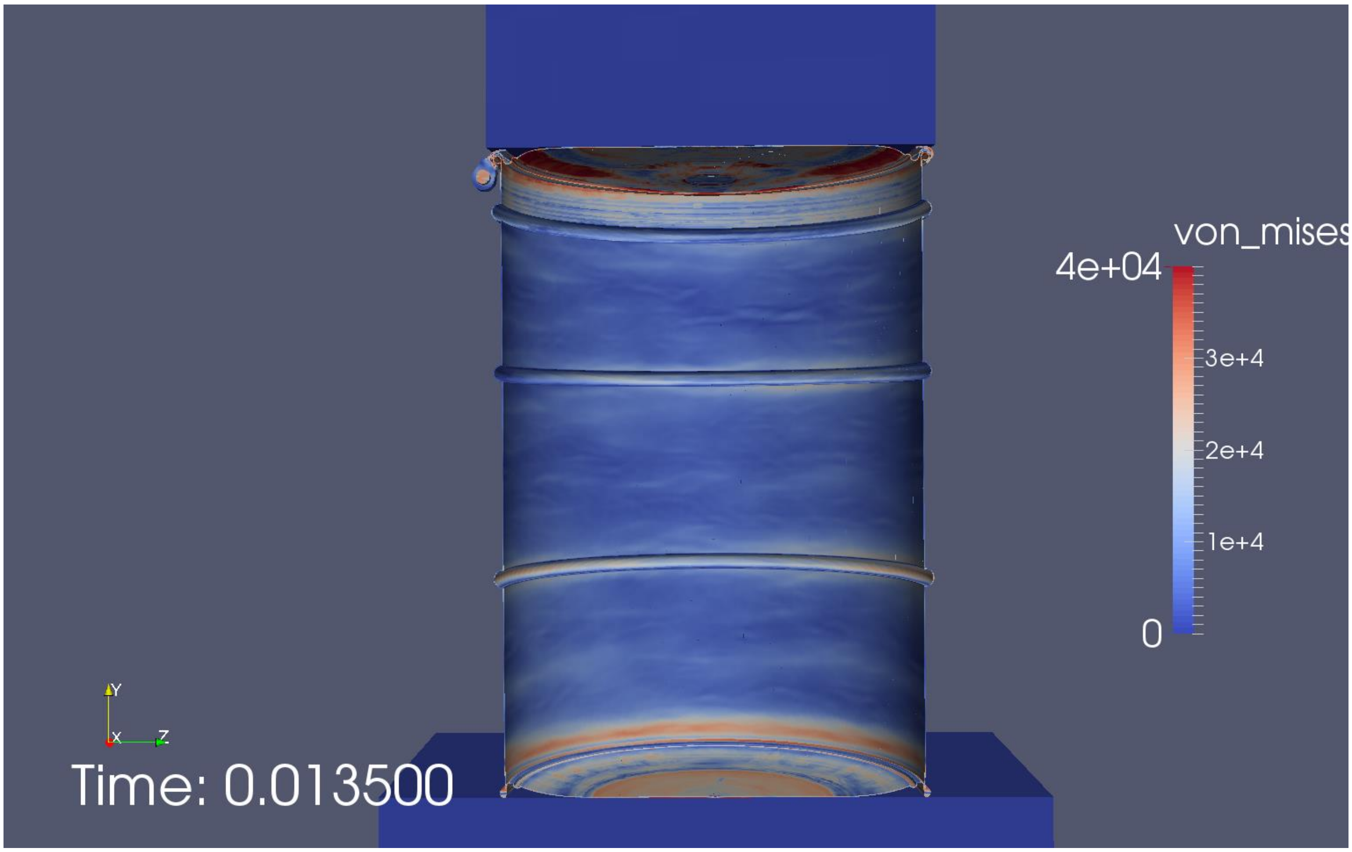


**Figure 17.** Analysis results for case with test properties, "fast" loading with maximum ramp pressure of 75 psi, and surrogate cask on top.

## Discussion

Further discussion of a number of topics are provided below.

*Influence and significance of potential material property variation*: The drum's are required to meet minimum property requirements. This ensures a minimum strength of the drums. However, it does not preclude the manufacturer from using material that exceeds the minimum specified. For example, the minimum specified yield strength of the ASTM A1008 steel used for the drums is 29,000 psi. The tested value for the drum material tested and presented above is 40,000 psi. The strength of the drums likely varies and this could influence the failure (lid opening pressure) under pressure loads such as those examined in this study. However, as these analyses have shown, the failure modes would be similar. For the "fast" loading cases the opening pressure of the drum did not vary for the runs with the initial estimate for properties (based on the minimum specified tensile strength of the material) and the material properties from the drum obtained from LANL. For the "slow" loading case, the opening pressure varied from 35 psi to 57 psi. The maximum ramp pressure for the "slow" loading case had to be increased to get the drum to open during the analysis. Therefore, the rate of pressurization was also varied between the two analyses. See Table 1 below for a summary of the analysis results.

*Influence of MgO on the opening pressure and failure of the drums*: The only analysis effort to account for the MgO on top of the drums was the inclusion of a uniformly distributed pressure across the top of the drums that accounted for the weight of the MgO. This resulted in a pressure of approximately 1.5 psi acting against the internal pressure. Therefore, it had relatively little influence on the resulting failure pressure. This does not account for any inertial forces that would be generated during a dynamic event. The MgO on top of the drums might have also influenced the location of the drum opening (e.g. if it is not evenly distributed across the top of the drum). However, no analyses were performed with anything other than a uniformly distributed load.

*Influence of rate of pressurization and maximum ramp pressure*: Analyses were conducted varying the time to maximum ramp pressure and the magnitude of maximum ramp pressure (See Figures 5 and 6). The results suggest that the relationship between the opening pressure and the time to maximum ramp pressure results in an increase in the opening pressure when the pressure ramps up at a higher rate. The opening pressures are a maximum for the cases where the time to maximum ramp pressure was 0.01 seconds. The analyses where this was extended to 0.015, 0.025, and 0.035 resulted in a significant decrease in the opening pressure. If the time to maximum ramp pressure was increased all the way to 0.1 seconds the opening pressure was the lowest of all the analyses (35 psi for the originally estimated properties). For analyses where the maximum ramp pressure was set at 150 psi and a time to maximum pressure of 0.01 seconds, there is significantly more deformation of the lid than when the time to maximum pressure is increased to 0.1 seconds. The pressurization in such a short time results in substantial deformation of the lid prior to the lid opening. Therefore, the deformation of the lid might provide an indication of the rate of the pressurization. See Table 1 for a summary of the results.

**Table 1**. Result exploring maximum ramp pressure vs. time to maximum pressure.

| Material Property Set | Loading Case | Maximum Ramp Pressure (psi) | Time to Maximum Ramp Pressure (sec) | Lid Opening Pressure (psi) |
|---|---|---|---|---|
| Initial Estimate | fast | 150 | 0.01 | 75 |
| Initial Estimate | Slow | 50 | 0.1 | 35 |
| Initial Estimate | Slow (w/ surrogate drum) | 50 | 0.1 | 46 |
| Initial Estimate | Slow | 150 | 0.1 | 38 |
| Initial Estimate | fast | 150 | 0.025 | 45 |
| Initial Estimate | fast | 75 | 0.015 | 45 |
| Initial Estimate | fast | 75 | 0.025 | 38 |
| Initial Estimate | fast | 75 | 0.035 | 38 |
| Tested | fast | 75 | 0.01 | 75 |
| Tested | Fast (w/ surrogate drum) | 75 | 0.01 | n/a |
| Tested | slow | 50 | 0.1 | n/a |
| Tested | slow | 75 | 0.1 | 57 |
| Tested | Slow (w/ surrogate drum) | 50 | 0.1 | n/a |
| Tested | Slow (w/ surrogate drum) | 75 | 0.01 | 66 |

*Deformation of the lid and possible cause for the lid remaining open after pressurization*: As discussed above, due to the small time-step of the analyses and the significant run-time associated with these analyses, performing analyses of a long enough duration to examine what happens after the lid opens was not completed for this study. However, there are two possible reasons for the lid remaining open after a pressurization event. One is that the lid undergoes plastic deformation during the pressurization, which results in permanent deformation of the lid. All of the analyses showed some plastic deformation in the lid.

The analyses with a faster pressurization and especially the cases with the fast pressurization and highest value of ramp pressure have the most plastic deformation. The second reason the lid might not have closed after the pressurization event is that the closure ring is still under strain (preload); and if it only came partially off, there would be significant force where the bottom edge of the closure ring was crossing the lip of the drum. The lid could be essentially “cantilevered” from the supporting portion of the closure ring that is still seated on the drum body lip and at the intersection where the closure ring is crossing the drum body lip. There should be no expectation of a symmetric release or deformation of the lid. This would further prevent the lids from settling back into their original position.

An example of the permanent deformation of the lid can be seen from the tests conducted by LLNL shown in Figure 18 (Hasegawa et al. 1993).

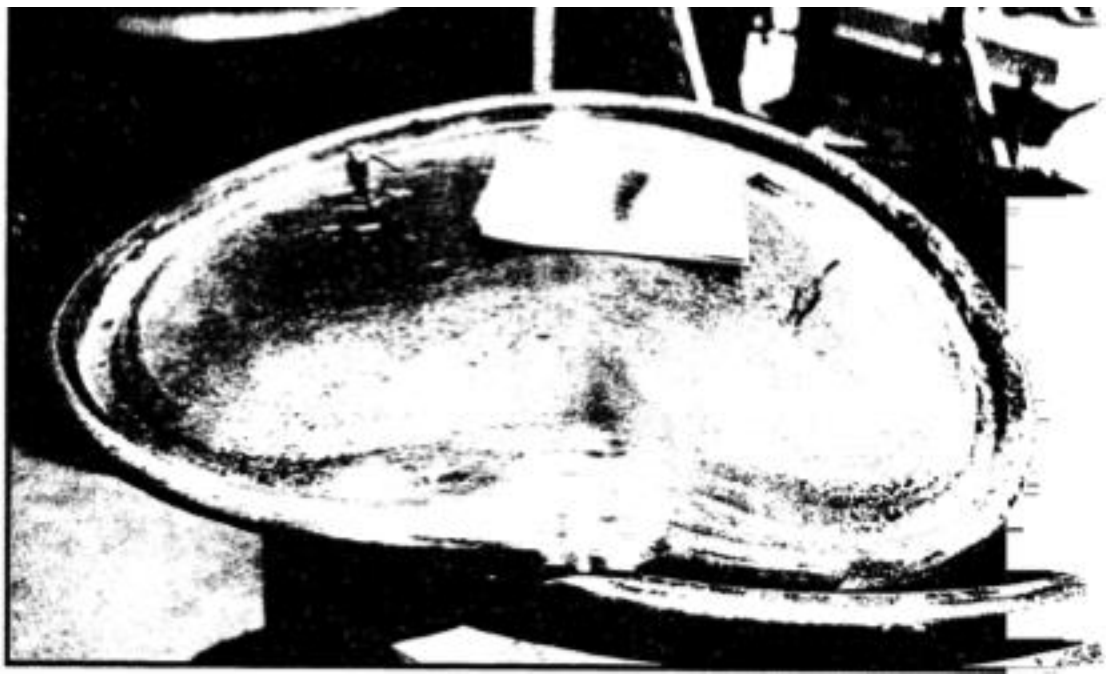

**Figure 18.** Permanently deformed lid from fire test (reproduced from Hasegawa et al. 1993)).

*<u>Drum geometric variations and lid closure preload and their influence on the results</u>*: Some analyses to examine the influence of drum geometric variations (thickness) and the influence of the closure ring preload were pursued. However, the initial analyses were not conclusive and due to time constraints the issues were not pursued further. The main reason for this is the lack of knowledge on the drum closure ring strain when closed per procedure. This likely has a significant influence on the calculated opening pressure from these analyses. Without a better understanding of the strain in the closure ring, it was not felt it was advisable to pursue some of these issues. There is uncertainty regarding how consistent the closure ring strain is from drum to drum. An improved understanding of this is advisable prior to pursuing further mechanical modeling with respect to predicting opening pressure.

*<u>Location of the initial drum opening and the orientation with drum plugholes</u>*: Some preliminary analyses were conducted investigating the orientation of the plugholes and the lid opening location. However, this was not pursued as a major area of investigation. However, it does appear that the plugholes could influence the location of the opening. For all of the analyses presented in this document, the lid was orientated in the same direction. Since the plugholes provide some stiffness to the lid, if the lid is rotated with respect to the bolt flanges on the closure ring, it might shift the location of the initial opening when the drum is over

pressurized. Further investigation in the room of the accident should attempt to note the location of the drum plugholes.

## Summary and Key Conclusions from Analyses

Over a relatively short period of time (several months) a finite element model of a WIPP drum was developed and analyses were conducted to support an investigation of the February 14th 2014 event. Uncertainty surrounding the closure ring tightness precludes some quantitative insights. However, a number of conclusions can be drawn from the study and are presented below:

1. Analysis of pressurization of the drums show that the lid will open at pressures between 35 and 75 psi for cases analyzed here. This calculated failure pressure is of the same order as the manufacturer's specifications and previous pressurization test data. No analyses showed the drum rupture on its sidewall and one would not expect that to happen from this type of a pressurized event. Only a blast load that reached a high enough load to fail the metal sidewall prior to applying a load to the top or bottom of the drum could rupture the sidewall prior to the lid opening. The pressurization tests at LANL and Savannah River sites discussed above all resulted in failures at the top or bottom of the drums.
2. The deformation behavior of the lid and the subsequent venting varies depending on the rate of pressurization. The analyses show significant plastic deformation of the lid. A faster loading results in more deformation of the lid. Therefore, the lid will likely remain deformed after the event and not return to its pre-pressurization state.
3. The analyses suggest the initiation of the lid opening will occur at the opposite side of the bolt on the bolt closure ring. The orientation of the plugholes in the lid will likely have some influence on this. In addition, the tests at LANL and the analyses suggest for "fast" loading cases the lid will deform and begin to vent near the bolt ring when there is large deformation of the lid. This is prior to the lid ejecting off the drum.
4. Analyses examining a pressurization of a drum with a surrogate drum on top suggest that the drums could vent even with a large object on top of it. It takes a higher pressure to open the lid for these cases. The drums could also pressurize and not open the lid. Therefore, if the lid does not open and the pressure is not released, they could remain under pressure.

## References


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Sierra/SolidMechanics, Sierra/SolidMechanics 4.34 User's Guide, Sandia National Laboratories, Albuquerque, NM, 87185.

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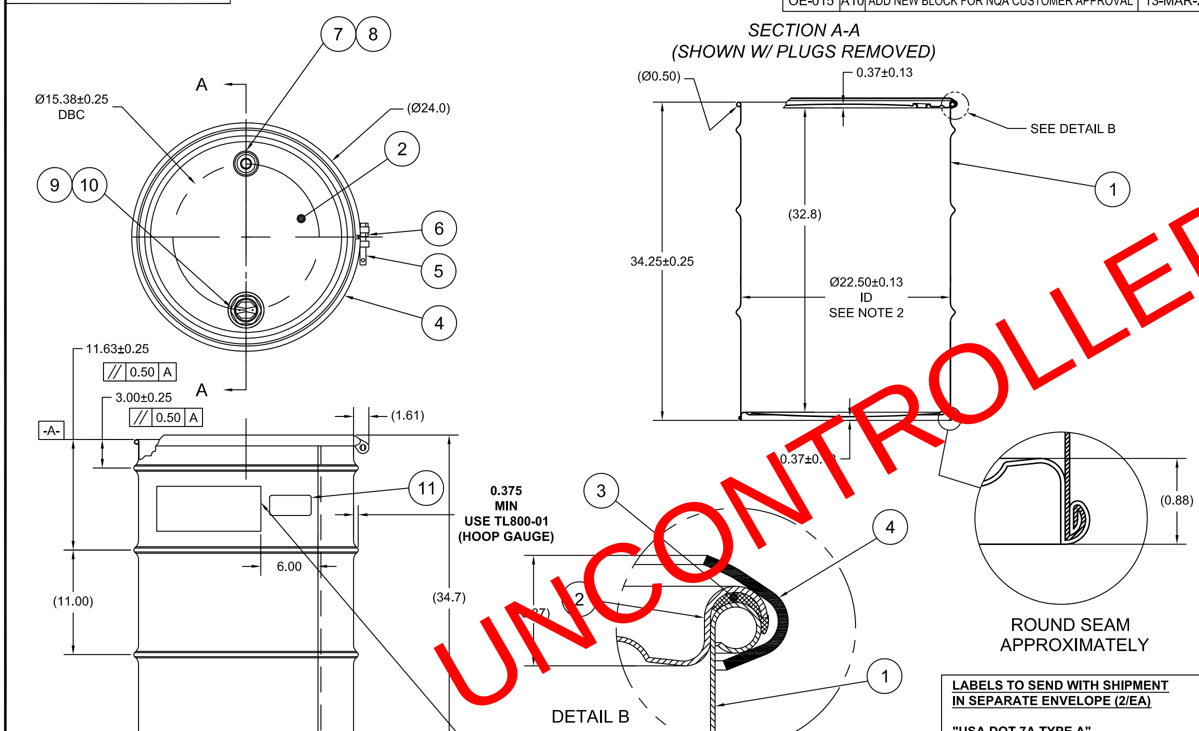
# Appendix

**WIPP Drum Drawings**

CQ5508L-LANL1

| ECN # or INIT | REV | DESCRIPTION | DATE |
|---|---|---|---|
| OE-015 | A10 | ADD NEW BLOCK FOR NQA CUSTOMER APPROVAL | 13-MAR-2014 |

| ECN # or INIT | REV | DESCRIPTION | DATE |
|---|---|---|---|
| LJT | A3 | WAS BALLON #9 (CLERICAL ERROR) | 14-JUL-2008 |
| LJT | A4 | CORRECTED STENCIL LOCATION (per DRUM DESCRIPTION) | 10-FEB-2009 |
| OE-001 | A5 | CLERICAL ERROR | 06-MAR-2009 |
| OE-002 | A6 | SEE ECN (per NEW QUALITY POLICY) | 30-APR-2009 |
| OE-004 | A7 | ADJUSTED THICKNESS TOLERANCE | 28-MAY-2009 |
| OE-010 | A8 | SEE ECN #OE-010 (NEW PART NUMBER) | 29-MAR-2012 |
| OE-003 | A9 | CORRECTED LABEL NOTE | 17-APR-2013 |




STENCIL THE FOLLOWING IN 1/2 INCH BLACK CHARACTERS
**6in TO THE LEFT OF WELD SEAM:**

[CUSTOMER PO NUMBER]
[LOT NUMBER]
[SERIAL NUMBER]

(Ø23.0)
SEE NOTE 2

UN NUMBER EMBOSSED ON BOTTOM OF DRUM
½" CHARACTERS READING:
UN/1A2/X430/S/YR
UN/1A2/Y1.5/175/YR
1.5 *

TARE WEIGHT:
60 lbs

BEST PRINTED ON B-SIZE PAPER

(YR = YEAR OF MANUFACTURE)

## NOTES:

1. THESE DIMENSIONS REPRESENT DRUM AFTER BEING PROPERLY ASSEMBLED AND CLOSED PER SKOLNIK CLOSING INSTRUCTIONS
2. TO DETERMINE GREATER ACCURACY OF ANY DIAMETRIC DIMENSION, MEASURING OF CIRCUMFERENCE IS REQUIRED
3. CONSTRUCTION per 49 CFR §178.504 (b)

## MATERIAL:

1. DRUM BODY AND COVER CRCQ CARBON STEEL PER ASTM A1008 OR ASTM A568 OR EQUIVALENT
2. MATERIAL THICKNESS 1.5mm (0.0543 - 0.0590, 16 GAUGE)
3. GASKET MAT'L PER ASTM D1056

## FINISH:

1. EXTERIOR DRUM ALL WHITE (LQ10020)
2. INTERIOR DRUM BODY AND COVER LINED W/EPOXY PHENOLIC COATING 0.6 MIL MIN DFT (LQ50007)

**LABELS TO SEND WITH SHIPMENT IN SEPARATE ENVELOPE (2/EA)**

**"USA DOT 7A TYPE A"**
**"RADIOACTIVE MATERIAL"**
**"GROSS WEIGHT LIMIT 935 POUNDS"**

| ITEM | P/N | DESCRIPTION | QTY |
|---|---|---|---|
| 11 | | UN DURABLE LABEL | 1 |
| 10 | FR2010 | FLANGE 2 RIEKE VGII EP/PH | 1 |
| 9 | PR2010 | PLUG 2 RIEKE VGII EP/PH BUNA GASKET **MUST BE BUNA GASKET** | 1 |
| 8 | FR3010 | FLANGE 3/4 RIEKE VGII EP/PH | 1 |
| 7 | PR3010 | PLUG 3/4 RIEKE VGII EP/PH BUNA GASKET **MUST BE BUNA GASKET** | 1 |
| 6 | NT5800NQA | NUT 5/8-11UNC HEX JAM NUT | 1 |
| 5 | BT5840.13NQA | BOLT 5/8-11UNC X 4 LONG, 11/32@1/2 FTE | 1 |
| 4 | RBH2212 | BOLT RING (HP) 55G 12GA 5/8 LUG | 1 |
| 3 | GE5500 | GASKET IN-COVER D EPDM | 1 |
| 2 | P2215L | COVER, Ø22.50 ID CRCQ STEEL | 1 |
| 1 | | 55 GALLON DRUM BODY AND BOTTOM | 1 |

| UNCONTROLLED | CONTROLLED |
|---|---|
| ✓ | |

PRELIMINARY APPROVAL X
APPROVED FOR FABRICATION SB
REVISED FOR FABRICATION SB
3/14/2014 DATE SB INITIALS

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| MFG | DRW | CHK |
|---|---|---|
| BR | LJT | JG |
| | SLS: DR | QA: MD |
| | APR: BH | |
| | FILE CREATED IN: AutoCAD 2002 | |

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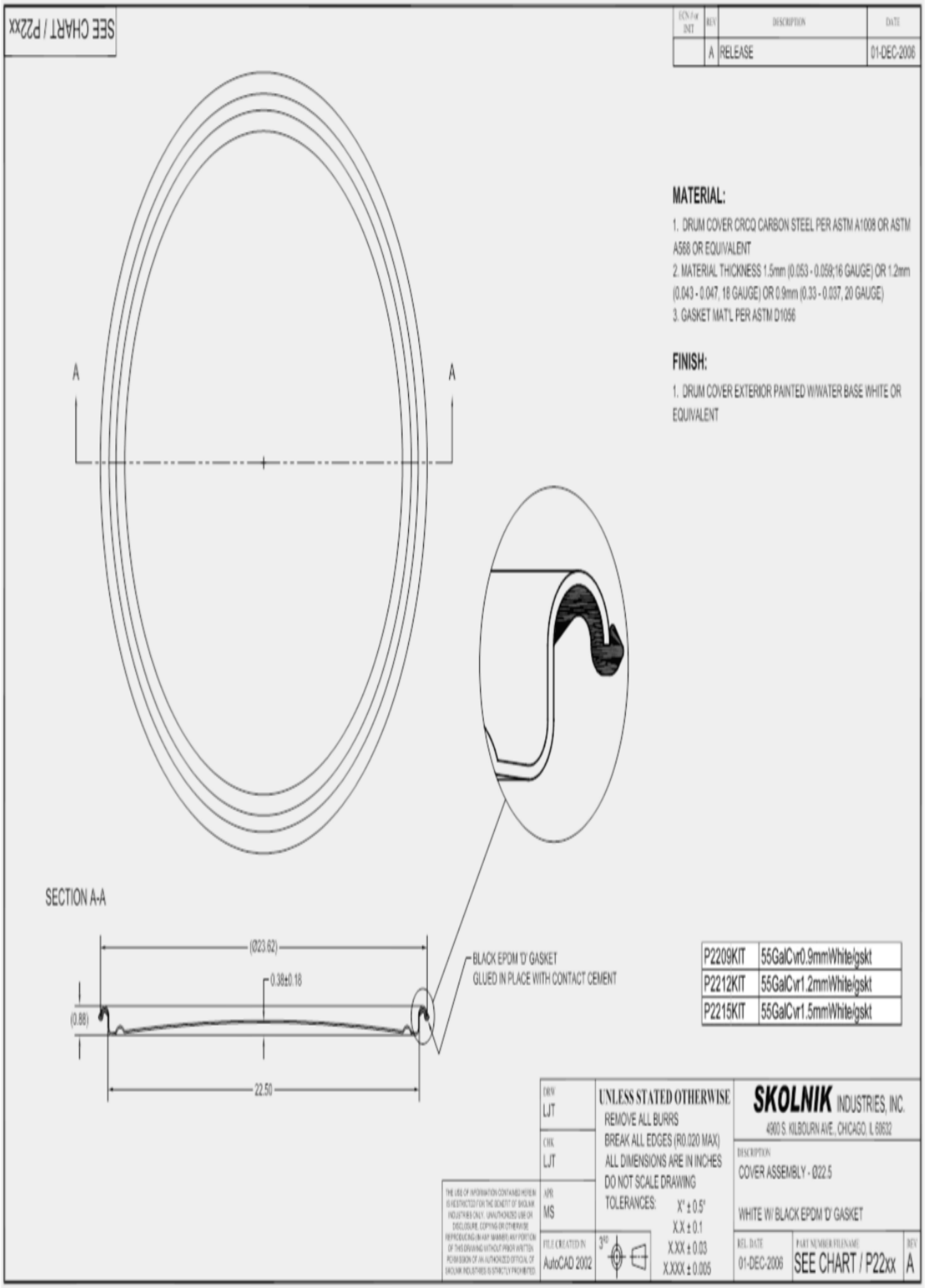
TOLERANCES:
FRACTIONS ±1/4
X° ± 3°
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.030
3RD

**SKOLNIK** INDUSTRIES, INC.
4900 SOUTH KILBOURN AVENUE, CHICAGO, IL 60632

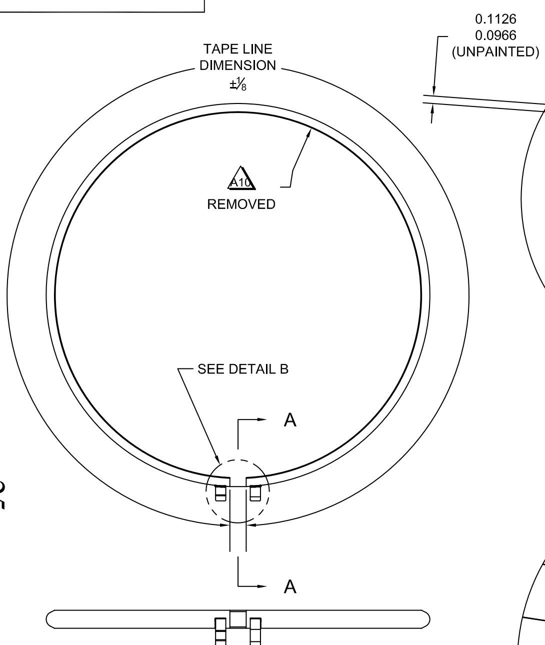
DESCRIPTION
55 GALLON OPEN HEAD DRUM
1.5 - 1.5 - 1.5 CRCQ
1A2/X430/S & 1A2/Y1.5/175

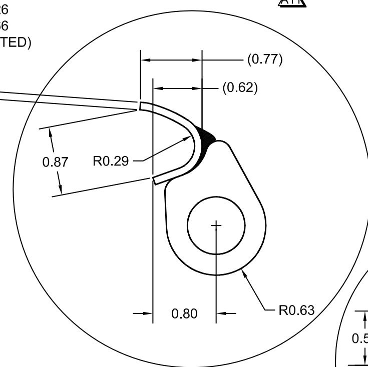
| REL. DATE | PART NUM. / FILENAME | REV |
|---|---|---|
| 17-MAR-2008 | CQ5508L-LANL1 | A10 |

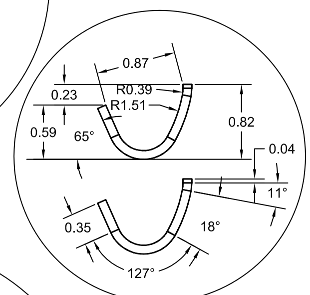
| A10 | CUSTOMER # | SPEC # (IF APPLICABLE) | APPROVED BY | via EMAIL/FAX DATE |
|---|---|---|---|---|
| | HALL035 | CQ5508L-LANL1 Rev A10 | Bill Waters | Email 3/13/14 |

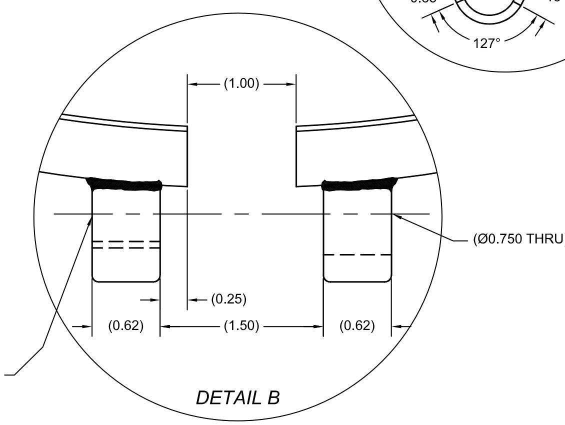

ECN # or INIT
REV
DESCRIPTION
DATE
A
RELEASE
01-DEC-2006
MATERIAL:
1. DRUM COVER CRCQ CARBON STEEL PER ASTM A1008 OR ASTM A568 OR EQUIVALENT
2. MATERIAL THICKNESS 1.5mm (0.053 - 0.059;16 GAUGE) OR 1.2mm (0.043 - 0.047, 18 GAUGE) OR 0.9mm (0.33 - 0.037, 20 GAUGE)
3. GASKET MAT'L PER ASTM D1056
FINISH:
1. DRUM COVER EXTERIOR PAINTED W/WATER BASE WHITE OR EQUIVALENT
A
A
SECTION A-A
(Ø23.62)
0.38±0.18
(0.88)
22.50
BLACK EPDM 'D' GASKET
GLUED IN PLACE WITH CONTACT CEMENT
P2209KIT 55GalCvr0.9mmWhite/gskt
P2212KIT 55GalCvr1.2mmWhite/gskt
P2215KIT 55GalCvr1.5mmWhite/gskt
DRW LJT
CHK LJT
APR MS
FILE CREATED IN AutoCAD 2002
UNLESS STATED OTHERWISE
REMOVE ALL BURRS
BREAK ALL EDGES (R0.020 MAX)
ALL DIMENSIONS ARE IN INCHES
DO NOT SCALE DRAWING
TOLERANCES: X° ± 0.5° X.X ± 0.1 X.XX ± 0.03 X.XXX ± 0.005
SKOLNIK INDUSTRIES, INC.
4900 S. KILBOURN AVE., CHICAGO, IL 60632
DESCRIPTION
COVER ASSEMBLY - Ø22.5
WHITE W/ BLACK EPDM 'D' GASKET
REL. DATE 01-DEC-2006
PART NUMBER/FILENAME SEE CHART / P22xx
REV A
SEE CHART / P22xx

RBHxx

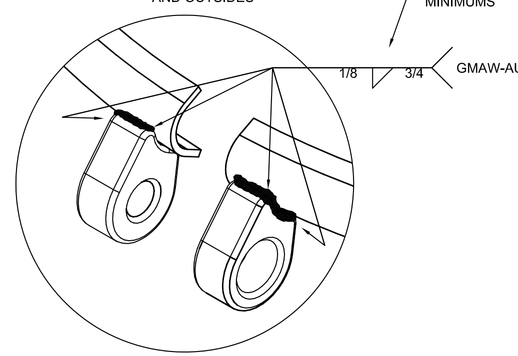



RING ENDS AND LUGS ARE PARALLEL AND HOLES ARE CONCENTRIC WHEN IN THIS POSITION




| ECN # or INIT | REV | DESCRIPTION | DATE |
|---|---|---|---|
| | A | RELEASE | 12-OCT-2006 |
| LJT | A1 | ADD'D TAPE LINE DIM FOR RBH1812 DRAWING # WAS RBH0000 | 22-DEC-2006 |
| LJT | A2 | ADD'D TAPE LINE DIM FOR RBH2612 | 12-JAN-2007 |
| LJT | A3 | WAS 12 & 13 GA, CLERICAL ERROR | 23-FEB-2007 |
| LJT | A4 | UPDATED FOR AWS STANDARD | 13-JAN-2010 |
| OE-001 | A5 | CLERICAL ERROR | 13-FEB-2010 |
| LJT | A6 | UPDATED | 10-MAR-2010 |
| LJT | A7 | UPDATED FOR 12GA RANGE INDUSTRY STANDARD | 20-MAY-2011 |
| OE-001 | A8 | CORRECTED WELDMENTS | 15-SEP-2011 |
| LJT | A9 | ADDED WELDING NOTE & CORRECTED LUG MAT | 18-OCT-2011 |
| OE-001 | A10 | ADD'D NOTE 2 & REMOVED SURFACE MARKING NOTE & CORRECTED SUPPLIER NOTATION ERROR | 28-NOV-2012 |
| OE-001 | A11 | CLERICAL ERRORS | 07-DEC-2012 |

## NOTES:

1) WELDED per AWS D1.3
2) INCOMING INSPECTION PERFORMED WITH TL878-04 (IF PAINTED) OR TL878-04-NP (IF UNPAINTED)

## MATERIAL:

RINGS: 12 GAUGE ASTM A568
LUGS: CARBON STEEL

## FINISH:

POWDER COATED QUARRY GRAY PER DUPONT RLH-617-S8
FILM THICKNESS: 1.8 -2.2 MIL (ALL SURFACES EXCEPT THREADS)

REFERENCE DRAWINGS
DRUM PARTS MIDWEST:
884a.dwg, 125517hhp.dwg

BEST PRINTED ON B-SIZE PAPER

| P/N | DESCRIPTION | TAPE LINE DIMENSION |
|---|---|---|
| RBH2612 | BOLT RING (HP) 79-96G 12 GA 5/8 LUG | 86.0 |
| RBH2212 | BOLT RING (HP) 55G 12 GA 5/8 LUG | 75 1/16 |
| RBH1812 | BOLT RING (HP) 20-30G 12 GA 5/8 LUG | 61 5/8 |

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| | |
|---|---|
| DRW LJT | CHK JD |
| SLS DR | QA GF |
| APR MG | |
| FILE CREATED IN AutoCAD 2002 | 3RD |

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X° ± 3°
X.X ± 0.2
X.XX ± 0.10
X.XXX ± 0.030

**SKOLNIK** INDUSTRIES, INC.
4900 SOUTH KILBOURN AVENUE, CHICAGO, IL 60632

DESCRIPTION
BOLT RING (HP), 12 GA CARBON STEEL
5/8-11 THREADED LUGS
FOR Ø18-1/4, Ø22-1/2, Ø26 DRUMS

| REL. DATE | PART NUM. / FILENAME | REV |
|---|---|---|
| 22-AUG-2006 | SEE BOM / RBHxx | A11 |

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